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CONTINUOUS CASTING INSTALLATION FOR THE ELECTROMAGNETIC ROTATION OF MOLTEN METAL MOVING INSIDE THE NOZZLE

The present invention relates to the continuous casting of metals, particularly steel, employing a submerged casting nozzle that dips into a mold placed thereunder. More precisely, the invention relates to the induction of axial rotation of the liquid metal flowing through such a nozzle between the pouring tundish and the mold.

It is known that inducing axial rotation of the metal already within the casting nozzle is a recommended means of controlling the flows into the mold, by modifying the distribution of inclusions and gas bubbles present in the liquid metal before it enters the mold. In this way it is possible:

- to reduce, or even eliminate, the deposition of inclusions along the inner wall of the nozzle and, in the case of a nozzle with lateral outlets for the casting of slabs, in these outlets and in the bottom of said nozzle;
- to greatly reduce the depth of penetration of inclusions and gas bubbles in the liquid well of the product during casting, and therefore also the risk of them being trapped on the inside curved face for products cast on a curved casting machine;
- to reduce the speed of flow of the liquid metal beneath the meniscus and the fluctuations in the level of said meniscus; and
- to limit flow instabilities, of the jet swing type, in the mold by having a "gyroscopic" effect on the flows in the nozzle.

The induction of rotation of the flows in the casting nozzle thus appears to be an effective means for preventing the appearance of visible surface flaws, of the blister and exfoliation type, on cold-rolled strips of grades of steel for automobile application and of packaging steel. This technique therefore means fewer crack repair operations on continuous cast slabs (reduction or even elimination of exfoliation-type surface flaws on strips), elimination of downgrading and of lawsuits in the case of blister-type flaws, and also

increased productivity of casting machines by having longer runs and higher casting rates.

The induction of the rotation of the liquid metal in the casting nozzle has already been proposed using various types of actuator. Basically, two types of actuator may be distinguished, namely "passive" actuators and "active" actuators.

Passive actuators use *inter alia* modifications in the design of the internal wall of the nozzle (for example, spirals), components, such as a propeller, helicoidal internal nozzle, etc., which are fitted into the actual body of the nozzle, or modifications in the upper part of the nozzle at the join with the tundish (for example, an acceleration cone) or else modifications in the actual component for regulating the metal flow rate in the nozzle. The major drawbacks of this type of actuator are that the rotation speed generated is directly dependent on the flow rate of the metal passing through the nozzle and that preferential sites for the deposition of inclusions in the nozzle are formed, hence the potential increase in the risk of the nozzle being blocked.

Active actuators are essentially of electromagnetic nature – a static annular electromagnetic inductor of the polyphase type closely surrounds the nozzle over a portion of its length and generates a magnetic field that rotates about the casting axis, intended to cause the liquid metal present in the nozzle to undergo axial rotation therewith. If required, the reader will find examples described in the documents JP 06 023498 or JP 07 108355 or else JP 07 148561.

However, the electromagnetic devices proposed hitherto are for the most part based on the technology of linear stators that generate a tangential rotating field operating at a low, or even very low, frequency (<10 Hz). In particular, these devices have the drawbacks of:

- generating rotation speeds that are often too low, owing to the current frequencies used, to obtain the desired effects (for example, for a 4 Hz three-phase current usable for a nozzle inside diameter of 80 mm, the maximum theoretical rotation speed is 80 rpm);
- generating, in the liquid metal, a force field that is highly concentrated

close to the inner wall of the nozzle, this having the consequence of creating a region of greatly reduced pressure in the central portion of the nozzle where the metal is therefore accelerated vertically downward; and

- having to operate with high electric currents (>300-500 A), which results in devices that are large in size, so as to be able to cool them, and therefore not easy to fit onto a continuous casting machine and also requiring the use of a very expensive electrical generator.

Other devices are based on a traversing magnetic field, therefore based on wound salient poles with one pair of poles per phase facing each other on either side of the nozzle axis. The invention falls within this category. They obviate some of the aforementioned drawbacks, in particular the central reduced-pressure phenomenon. However, the confined space allied with necessarily high stored electrical power, together with the desirable reduction in the airgap by reducing the distance between the inwardly salient pole tooth that projects beyond the winding and the nozzle, in order to maximize the electromagnetic coupling, inevitably result in fact in a lower energy efficiency at the same time as a certain degree of possible disorganization in the rotational movements of the metal, in particular as a result of the risk of spurious bridging of the magnetic flux between poles corresponding to different phases of the power supply that are too close.

The object of the present invention is to propose a solution for electromagnetically inducing rotation of the liquid metal within a casting nozzle but does not have the drawbacks of the known solutions.

For this purpose, the subject of the invention is an installation for the continuous casting of metals, particularly steel, in which the submerged nozzle, via which the molten metal to be cast arrives in the mold from a tundish located thereabove, is surrounded by a static annular electromagnetic inductor having a magnetic field that rotates about the casting axis and is intended to force the molten metal to rotate axially therewith, said inductor being of the polyphase traversing-magnetic-field type, which inductor is provided with a pair of poles per phase and each pole of which is formed by an electrical winding wound around an inwardly salient pole tooth that terminates in a pole face placed

facing and close to the nozzle, the pole teeth being connected together by an outer peripheral magnetic yoke that closes the magnetic flux circuit, said installation being characterized in that each pole tooth has a lateral taper (for example, a bevel) at the end of its salient part, that increases the distance by which the pole faces are separated from one another.

According to an advantageous embodiment, the annular inductor is formed as two articulated half-shells that can pivot, enabling them to be closed up around the nozzle.

As will doubtless have been understood, the invention employs what is called a "traversing" magnetic field, that is to say a field that passes through the axis of the nozzle without a manifest reduction in its intensity between the edge and the center of the nozzle.

Thanks to the technological basis adopted, namely that with a pair of poles per phase of the power supply that supplies power to an annular polyphase inductor having wound salient poles distributed around the nozzle, the rotating magnetic field produced is of the desired "traversing" type. In other words, at each instant, the casting axis is at the center of the airgap of the inductor and the field produced prospers in this airgap by passing through the casting axis so as, from a given magnetic pole, to rejoin the paired magnetic pole of opposite sign located opposite it but not beside it, as would be the case with an inductor having distributed poles or having several pairs of poles per phase.

It will be recalled that this type of technology is not in itself novel. It has even been quite widely used for inducing rotation in cast liquid metal, not within a nozzle but within the mold itself, and therefore in the case of rotors (i.e. the column of liquid metal) to be rotated having a much larger apparent diameter than that of the jet of metal in the nozzle and with a requirement of a correspondingly much lower angular rotation speed (see for example USP 4 462 458). Now, contrary to received ideas, it turns out that a transfer of this technology from mold to casting nozzle may, without necessarily involving a considerable reduction in installed power, be accompanied by a reduction in size of the inductor compatible with it being fitted around and as close as

possible to a casting nozzle provided that the "traversing", or in any case essentially "traversing", character of the magnetic field produced is maintained, and to do so without therefore impairing its necessary cooling.

It is precisely this that forms the idea at the basis of the invention, namely to succeed, without compromising the performance of the inductor, in preserving this "traversing" character of the field despite the compactness of the inductor and the minimization of the airgap by accepting a slight loss of magnetic mass located at chosen points on the salient poles, namely the edges of the active faces, in order to counteract the natural tendency of the magnetic field to propagate in the airgap along the paths of least reluctance by looping back between the adjacent poles closest to one another.

Tests carried out on steel have confirmed the ability of such an inductor to induce rotation of the metal flowing in a submerged nozzle under casting conditions that are much more severe than those encountered in industrial machines for casting blooms or slabs. These tests were carried out in fact with a nozzle of the straight type (single axial outlet that opens in the bottom) through which the metal flows at a mean speed of around 3.5 to 4.2 m/s, bearing in mind that in a nozzle for casting slabs, the mean output speeds are more between 1.5 and 2.0 m/s.

The invention will in any case be more clearly understood and further aspects and advantages thereof will become apparent from the description that follows, given by way of illustrative example and with reference to the appended plates of drawings in which:

- figure 1 is a diagram showing, seen in cross section, the inductor formed from two half-shells butted together, provided with its internal heat shield bordering the airgap;
- figure 2 is a diagram similar to the previous one, but intended to show the propagation of the lines of force of the traversing magnetic field in the airgap as frozen at any given instant in the operation of the inductor;
- figure 3 is a functional diagram showing the principle of how the two constituent half-shells of the inductor are articulated;
- figure 4 shows the velocity map of the liquid metal rotating within the

casting nozzle under the effect of the magnetic field in a cross-sectional plane of the nozzle;

- figure 5 shows the variation in the intensity B of the magnetic field in the airgap along a diameter D of the nozzle taken in a plane located at mid-height of the inductor; and
- figure 6 shows, corresponding to the representation of figure 5, the corresponding variation in the field of magnetic forces F_B along a diameter D of the nozzle in a radial profile R and in an orthoradial profile OR.

In these figures, the same elements are denoted by identical references.

As may be seen with reference to figures 1 to 3 together, the inductor 1 is a linear motor stator closed on itself, consisting for this purpose of two independent equal semitubular parts 2a and 2b (the half-shells). Each half-shell has three wound salient poles 3, the pole face 4 of which is turned toward the inside, these magnetic poles, made of stacks of soft iron laminations, being conventionally connected together by an external peripheral semitubular yoke 5a, 5b. The system is designed so that the two paired yokes butt together in the joining plane J when the inductor is in the closed working position shown in figures 1 and 2.

A cap 7a, 7b, also of corresponding semitubular shape, covers the inside of the pole faces of each half-shell and forms, once the inductor is in the closed position, a heat shield 7 that closely surrounds the casting nozzle. This heat shield is desirable for the electrical windings 3 of the inductor with regard to the radiation emitted by the casting nozzle 8 shown in figure 3, which channels the stream of molten metal into the mold. Details about the possible construction of this shield will be given later.

The electrical winding 6 of each wound pole 3 is connected to one phase of a three-phase power supply (not shown) intended to deliver the primary current for the inductor. When the inductor is in the closed position, any salient pole of one of the half-shells 2a diametrically faces a salient pole of the other half-shell 2b. These two poles form a "pair of poles" in the sense that they are both connected to the same phase of the power supply, but in phase opposition (for example via a different winding direction) so that, at each instant, their

active faces are of opposite signs. This condition is necessary so that the magnetic field produced is of the traversing type.

The poles 3 and the magnetic flux return yoke 5a, 5b are laminations made of oriented-grain Fe-Si sheets with an initial thickness of 0.3 mm so as to minimize hysteresis losses. Their operational height (the height of the active face 4) is between 50 mm (the minimum value) and 500 mm, depending on the available space between the tundish and the top of the mold, between which the inductor will be placed. Their inside diameter (the diameter of the airgap) is of the order of the outside diameter of the casting nozzle increased by around ten millimeters, barely enough to maintain a separation but so as to ensure the best possible inductive coupling.

The primary windings 6 are formed from a large number (several hundred) turns of copper wire of very small diameter that can support high current densities (>10 A/mm^2). They are provided, within them, with water-cooled copper heat sinks (not shown).

These windings are supplied with three-phase currents of medium frequency ranging from 50 Hz to 600 Hz. In the proposed technology, it should be noted that operating at high frequency above 50 or 60 Hz, makes it possible, for constant current intensity, to increase the motor torque that the electromagnetic forces exert on the metal flowing through the nozzle. However, this option requires the use of a frequency converter unlike operation at the mains frequency (50 or 60 Hz).

As the diagram in figure 5 shows, this static motor that the inductor 1 constitutes can generate, in its airgap occupied by the nozzle, a transverse electromagnetic field (called "traversing" field) of high intensity (between 1000 and 1500 gauss) for low inductor current values (a few tens of amps).

This field, as may be seen in the diagram, is virtually uniform in the central portion of the airgap. This essential feature of the invention makes it possible to generate a force field in the liquid metal that decreases uniformly from the wall to the center, as the diagram in figure 6 shows. This makes it possible, as the velocity map of figure 4 also clearly shows, to induce rotation in the liquid metal with a speed that remains high even in the axial portion of the

nozzle. This specific feature is necessary in order to prevent too great a reduced pressure in the central portion of the nozzle where the metal would then have a tendency to “escape” and be subjected to a high downward acceleration, thus canceling out part of the beneficial effect of the rotational movement.

As is clearly apparent from figure 2, it is thanks to the tapered shape of the radial magnetic teeth 3 at their free end 4 (the pole faces) that, at any moment, the lines of force of the magnetic field in the airgap essentially connect two diametrically opposed poles and that only a residual portion of the field loops back between neighboring poles. This result, which is essential for implementing the invention, is obtained, despite the necessary compactness of the inductor, thanks to this tapered shape of the end of the poles, which means that, despite their coming closer together upon moving toward the center, the distance that separates their free ends, in pairs, remains sufficient to prevent substantial bridging of the field lines between them. It is this which, in the case of a small compact inductor, guarantees the high relative intensity of the magnetic field along the axis (cf. figure 5), in other words the necessarily “traversing” character of this field without which the invention does not produce the desired effects. As may be seen in figure 1, and more clearly visible in figure 2, this tapering shape of the radial teeth 3 is obtained by a bevel precut 12 of the ends of the laminations to be stacked in order to form them. The bevel angle is to be adjusted according to the outside diameter of the nozzle to be surrounded. However, the pole face 4 must not have an area less than half the cross section of the tooth 3 and the taper bevel 12 on the body of the tooth can start only at two-thirds of the way along the length. It is unnecessary to start before this, and it is even desirable to start it as late as possible so as to maximize the magnetic mass of the inductor.

By supplying the inductor via a resonant circuit, the intensity of the primary currents may be greatly increased. The proposed technique makes it possible in fact, within a wide primary current range, to very greatly increase the intensity of the electromagnetic field in the airgap, by increasing these currents to values well beyond the threshold current corresponding to magnetic

saturation of the yoke 5. This allows the magnetic field lines to be channeled and the intensity of this magnetic field in the airgap of the motor to be increased to the point where the latter reaches its saturation value in the yoke. Beyond this threshold value, it is the magnetic field generated by the inductor directly in the air that contributes to increasing the intensity of the field in the airgap of the motor.

In operation, the inductor is very close to the casting nozzle 8 (about 5 mm away from it), the outside temperature of the nozzle being around 1100 to 1200°C. It is therefore thermally protected from the radiation emitted by the nozzle by the thin segmented copper shield 7 that is cooled by water circulation and is transparent to the electromagnetic field thanks to this segmentation.

The construction of the inductor 1 as two independent semitubular parts 5a and 5b allows it to be easily fitted around the nozzle and removed at any moment without modifying the standard casting process. Again referring to figure 3, it may be seen that, in order to fit the inductor around the casting nozzle 8, it is advantageously held in place by a support consisting of two arms 9 articulated about a pivot spindle 10. The arms are driven by cylinders 11 which open and close them and exert a sufficient contact force (of greater than 200 kgf) between the yokes 5a and 5b of the two semitubular parts 2a and 2b once these are in abutment, as shown in figure 1. Firstly, close contact between the yokes 5a and 5b is necessary for good looping of the magnetic field lines between the two constituent parts of the inductor, and therefore necessary for good electromagnetic efficiency. Secondly, a high clamping force between the two half-tubes is necessary in order to prevent vibrations that would inevitably be generated by the oscillating electromagnetic forces.

It goes without saying that the invention is not limited to the exemplary embodiment described, rather it extends to many alternative and equivalent embodiments provided that its definition given by the appended claims is respected.